N86-23994

(NASA-CR-176725) REMOTE SENSING INVESTIGATIONS OF WETLAND BIOMASS AND PRODUCTIVITY FOR GLOBAL BIOSYSTEMS RESEARCH Final Technical Report, 1 Nov. 1982 - 1 Apr. 1986 (Delaware Univ.) 25 p HC A02/MF A01

Unclas
G3/43 05988

REMOTE SENSING INVESTIGATIONS OF WETLAND BIOMASS AND PRODUCTIVITY FOR GLOBAL BIOSYSTEMS RESEARCH

Final Technical Report

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302/451-2336

Grant Number: NAGW 374

Grant Duration: 1 November 1982 to 1 April 1986

Submitted To: Dr. M. Averner
NASA Headquarters
Office of Life Sciences
Code EBT-3
Washington, DC 20546

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
RESEARCH AND TECHNOLOGY RESUME

1 DATE PREPARED	15 April 1986
2 TITLE	Remote Sensing Investigations of Wetland Biomass and Productivity for Global Biosystems Research
3 NUMBER/CODE — a PROPOSAL	
3 NUMBER/CODE — b CURRENT	
4 PERFORMING ORGANIZATION	College of Marine Studies University of Delaware Newark, DE 19716
5 CONTRACT/GRANT NO	NAGW 374
6 DATE — a STARTING	11/1/82
6 DATE — b ANNIVERSARY	4/1/86
7 INVESTIGATOR'S NAME / TEL. NO	V. Klemas 302/451-2336
8 NASA ALT TECH MONITOR'S NAME / TEL. NO	
9 INSTITUTION CATEGORY CODE	

FISCAL YEAR	STATUS a	MANPOWER (MY) IN HOUSE b	S/C c	FUNDING (In K) IMS d	R/D e	TOTAL f
10. PRIOR						
11. CURRENT						
12. BUDGET						

13 DESCRIPTION *(a Brief statement on strategy of investigation. b Progress and accomplishments of prior year. c What will be accomplished this year, as well as how and why, and d. Summary bibliography)*

This research has been directed toward an understanding of the relationship between spectral radiance and plant canopy biomass in wetlands. The green components of a plant canopy interact most strongly with incident radiation, and changes in the architecture of the canopy alter the observed spectral radiance patterns. Plant biomass serves as an excellent integrator of the environmental factors encountered by the plant and can be used as an indicator for predicting soil redox, nutrient status, microbial activity, etc. The approach used has been to gather spectroradiometer data of wetland vegetation canopies in Thematic Mapper wavebands 3, 4 and 5, and to correlate this data with canopy and edaphic factors determined by harvesting. Under this grant, the following four specific tasks have been carried out:

(1) The relationship between spectral radiance and plant canopy biomass for major salt and brackish canopy types was determined, including comparison and modeling of diverse morphologic characteristics.
(2) Algorithms for biomass measurement in mangrove swamps were developed.
(3) The influence of latitudinal variability in canopy structure on biomass assessment of selected wetland plants was investigated.
(4) Brackish marsh biomass estimates were obtained from a low-altitude aircraft and compared with ground measurements.
(5) Annual net aerial primary productivity (NAPP) estimates computed from spectral radiance data were compiled for a *Spartina alterniflora* marsh and compared with harvest estimates.

Spectral radiance data were expressed as vegetation or infrared index values. Biomass estimates computed from the models were in close agreement with biomass estimates determined from harvesting during most of the growing season. Both dead biomass and soil background reflectance attenuated vegetation index biomass predictions, whereas only dead biomass reflectance attenuated infrared index biomass predictions. As a result, the infrared index yielded biomass means more similar to harvest biomass means in low live biomass areas, and the vegetation index yielded mean biomass estimates more similar to harvest biomass means in high live biomass areas.

NAPP estimates computed from spectral radiance data were generally within 10% of similar NAPP estimates computed from harvest biomass data. Considering the much larger number of biomass estimates which can be computed from spectral data collected with a radiometer as compared to the number which can be estimated by harvesting in an equal time period, remote sensing estimates of whole marsh biomass and NAPP appear to be more representative than estimates based on conventional harvesting techniques.

TECHNICAL MONITOR	TYPED NAME AND SIGNATURE	DATE
APPROVING OFFICIAL	TYPED NAME AND SIGNATURE	DATE

NASA FORM T43 DEC 74 REPLACES NASA FORM T8 WHICH IS OBSOLETE

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INTRODUCTION

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COMPARISON AND MODELING OF WETLAND CANOPY TYPES

The spectral characteristics of a variety of wetland plant species were investigated. The plants selected for study represented the most common marsh plants and considered the three most common plant morphologies: broadleaf, gramineous, and leafless. By considering the growth morphology of plants, we were able to eliminate the need for developing models for each individual plant species. Rather, we were able to study representatives of each morphologic group and extrapolate those models to other plant species of similar canopy morphology. The problem of different canopy architecture is not really a problem in salt marsh systems, but is a significant consideration in the mixed plant stands of the brackish marshes.

Modeling the relationship between spectral radiance indices and live aerial biomass in brackish marsh plant communities required consideration of diverse morphologic characteristics among plants residing in the same community. Figure 1 shows the linear relationship between vegetation index and total live biomass for a variety of wetland plants. Canopy architecture plays a decisive

role in the interception of incoming radiation and, therefore, is an extremely important consideration when interpreting spectral radiance signatures from wetland plant canopies. Iva, Polygonum and Solidago represent broadleaf canopies and exhibit rapid increases in vegetation index for relatively small changes in biomass. This characteristic suggests that the spectral index can become saturated rapidly. Structurally, these canopies maintain most leaf surfaces in the horizontal plane and generally form a complete canopy cover, reducing or eliminating the exposure of dead components or soil background to solar irradiance. This combination of canopy characteristics yields a very absorptive canopy in the red region and a very reflective canopy in the near infrared region, thus the high vegetation index relative to the amount of live biomass present.

The opposite extreme to the broadleaf canopy would be the leafless canopies represented by Salicornia and Scirpus. Both Salicornia virginica and Scirpus olneyi possess erect, leafless stems with most green tissue in the vertical plane, and primarily soil background and dead plant material in the horizontal plane. Normally these canopies are very open with soil surface characteristics potentially contributing greatly to the observed spectral radiance.

The third canopy type represented in Figure 1 is the gramineous canopy type of Spartina and Typha. Spartina alterniflora exhibits alternate leaves along the length of the stem, whereas Typha angustifolia has basal leaves. Both plants form canopies with portions of leaves in the horizontal and in the vertical plane. S. alterniflora exhibits a broad range of canopy configurations as a result of its wide environmental tolerance limits. Both plant canopies can maintain substantial quantities of dead material within the canopy. The amount of live leaf tissue determines to what degree dead material and soil background will influence spectral reflectance. Theoretically, the occurrence of flat leaves (portions of which may be horizontal) in the gramineous canopy would place them somewhere between the broadleaf and leafless canopies in terms of an increase in vegetation index value for an increase in biomass (i.e. an intermediate slope). In practice, this does not occur because the measured vegetation index represents the composite of reflectance from vegetation (live and dead) and the soil. In the case of the gramineous canopy, the dead vegetation and soil are oftentimes well-illuminated and contribute significantly to the measured vegetation index. The net effect is an attenuation of vegetation index increases with increasing biomass amount when compared to the other canopy types.

BIOMASS ESTIMATION OF MANGROVE SWAMPS

Several mangrove swamps on the Pacific coast of Costa Rica near Puntarenas were selected for study. Highly saline areas supporting dwarf black mangrove Avicennia germinans were sampled using a hand-held Mark II radiometer. Avicennia is probably the most abundant species of mangrove in Costa Rica and in the United States. Short canopies were selected initially to minimize logistical difficulties until we were sure that a reliable relationship between mangrove biomass and spectral radiance could be established.

Areas were selected randomly, but covered canopy heights ranging from 0.3m to 1.7m. Plots selected were measured with the radiometer, followed by harvesting a $1m^2$ area. Harvested material was returned to the laboratory and sorted into woody and leaf tissue. Plant material was dried in a 60°C oven to constant weight. Dried samples were weighed to the nearest 0.1g.

Radiometric sampling was accomplished using a Mark II radiometer configured to simulate bands 3, 4 and 5 of the Thematic Mapper (TM), and bands 5 and 7 of the Multispectral Scanner (MSS). Radiance data were collected at a height of 1.5m above the canopy, five times over every plot. The five replicates were averaged before further analysis. Radiance data were expressed as index values according to established procedures (Hardisky et al. 1983a,b).

A summary of initial correlation analysis is found in Table 1. As we expected, the only canopy parameter significantly correlated with radiance values was live leaf biomass. Mangrove canopies can be classified as broadleaf canopies, suggesting that most leaf surfaces are in the horizontal plane and that little biomass below the green canopy is illuminated. The TM vegetation index was the best spectral index for biomass quantification in the mangrove canopies. Figure 2 illustrates the relationship between vegetation index and live leaf biomass. Although the correlations between spectral radiance indices and live leaf biomass were significant, we expect to develop stronger relationships as our sampling effort continues. We are planning additional data collection from more dense (taller) mangrove canopies. We have fabricated an extension tower from which a radiometer can be suspended, allowing us to sample taller canopies. In addition, we plan to study even taller canopies from low-flying aircraft.

Wood biomass cannot be estimated directly from remote sensing data. We are exploring the possibility of estimating wood biomass based on the amount of leaf tissue. We are also collecting data on canopy height and tree diameter as possible ground measurements to be used in estimating wood biomass. Our present feeling is that leaf biomass is the principal component of net annual primary productivity (NAPP), and that the small annual increases in wood biomass could be inferred from analysis of the green components of the canopy.

TABLE 1

Correlation Coefficients Describing the Relationship Between Mangrove Canopy Parameters and Spectral Radiance Indices

Spectral[a] Radiance Index	Live Leaf Biomass	Woody Biomass	Total Biomass
TM VI	0.79*	0.32	0.38
TM II	0.70*	0.03	0.07
MSS VI	0.66*	0.30	0.35

[a]TM VI = Thematic Mapper, Vegetation Index, Bands 3 and 4.
TM II = Thematic Mapper, Infrared Index, Bands 4 and 5.
MSS VI = Multispectral Scanner, Vegetation Index, Bands 5 and 7.

*Denotes significance at the 0.05 probability level.

INFLUENCE OF LATITUDINAL VARIABILITY IN CANOPY STRUCTURE ON BIOMASS ASSESSMENT

One area of concern when using spectral radiance models for estimating biomass over large areas is the morphologic change of a plant species over latitude and the resultant effects upon biomass estimation. Some salt marsh plants like *S. alterniflora* and *S. patens* exist all along the eastern coast of the United States (Reimold 1977). Southern marshes are dominated by *S. alterniflora*, with northern marshes containing more *S. patens*. Since canopy morphology may vary with latitude, it is necessary to document specific morphological changes and to assess their impact upon spectral estimation of salt marsh biomass.

During 1983, coastal salt marshes were sampled for biomass and spectral radiance. Sampling sites included Sackville, New Brunswick; Wolfville, Nova Scotia; Hogg Bay, Maine; Plum Island, Massachusetts; Barnstable, Massachusetts; Mystic, Connecticut; and Lewes, Delaware. These sampling areas represented three distinct marsh types. The two Canadian sites were representative of the high tidal energy marshes of the Bay of Fundy. Marsh canopies (in particular, *S. alterniflora*) were tall and open with individual culms being somewhat spindly. This canopy structure is very similar to the high tidal energy marshes of the southeast (Georgia and South Carolina). The Maine, Massachusetts and Connecticut sampling sites contained a much more patchy and diverse flora. Canopies of *S. alterniflora* were full compared to Fundy marshes. The Delaware site also had more uniform canopy cover, but the marsh contained large monospecific areas of *S. alterniflora* similar to the Fundy marshes. Canopy structure changes were indeed evident; however, they appear to be related to the magnitude of the tidal range and to soil type (proportion of organic versus inorganic material) rather than to latitude.

A major goal of this research was to determine the feasibility of nondestructively estimating salt marsh biomass over a range of latitudes using spectral radiance data. Using regression models developed in a Delaware marsh, we compared spectral estimates of biomass to harvest estimates of biomass for the test sites (Table 2). Without modification of the existing models, the live biomass estimates from spectral data for short *S. alterniflora* were not very accurate. Examination of harvest versus spectrally estimated biomass suggests that the errors in estimation are not random. There was a systematic overestimation of live biomass at all the test sites. The remainder of the spectral data is now being analyzed. Since the errors do appear to be systematic, relatively simple modifications to the models may greatly improve biomass estimation capabilities. The low number of replicates at any particular site may have also contributed to the observed variability.

TABLE 2.

Comparison of Harvest Estimated and Spectrally Estimated Short *S. alterniflora* Biomass.

Location	Live[a] Biomass	VI Live[b] Biomass	II Live[c] Biomass	Total[d] Biomass	VI Total Biomass	II Total Biomass	n
Sackville, NB	356(91)	431(216)	607(114)	551(248)	729(177)	905(102)	8
Wolfville, NS	369(131)	646(344)	833(98)	446(174)	922(264)	1109(62)	5
Hogg Bay, ME	132(29)	224(26)	474(24)	342(38)	581(12)	831(10)	2
Barnstable, MA	373(41)	943(170)	820(87)	642(97)	1165(156)	1042(81)	3
Mystic, CT	402(84)	1022(517)	749(190)	928(160)	1244(484)	971(158)	3
Lewes, DE	451(50)	888(147)	830(140)	720(140)	1114(134)	1057(146)	4

[a]Live biomass is green leaf and stem biomass.

[b]VI live biomass is live biomass estimated using the vegetation index.

[c]II live biomass is live biomass estimated using the infrared index.

[d]Total biomass is all aboveground biomass (live and dead).

All values are mean biomass in grams dry weight per square meter with one standard deviation in parentheses.

BRACKISH MARSH BIOMASS ESTIMATION FROM THE GROUND AND FROM AIRCRAFT

Model Development

Gramineous canopies represented by two height forms of Spartina alterniflora and two stands of Typha angustifolia, a leafless canopy represented by S. olneyi, and a broadleaf canopy represented by a mixture of Acnida cannabina and Hibiscus moscheutos (Acnida/Hibiscus) were chosen for study. The tall S. alterniflora, one T. angustifolia, the S. olneyi and the Acnida/Hibiscus stands were located in Old Mill Creek marsh. A short S. alterniflora stand was located in Canary Creek marsh, and an additional T. angustifolia stand was located along the Broadkill River. All of these sites are near Lewes, Delaware. The T. angustifolia stand in Old Mill Creek was relatively small (<.5 ha), so the much larger T. angustifolia stand along the Broadkill River was added to the sampling scheme. As will be discussed shortly, each of the plant communities was also monitored from low-altitude aircraft. The small size of the Old Mill Creek stand required precise flightlines, which were sometimes difficult. The additional T. angustifolia area served as a backup in case data from the smaller area could not be obtained.

Each of the six areas (short and tall S. alterniflora, two T. angustifolia, S. olneyi, and the Acnida/Hibiscus) were visited monthly from May through August 1982. Three plots at each area were selected at random and ground-based spectral radiance data were collected, followed by harvesting. All plant material (including standing dead) within a $0.25m^2$ frame was clipped at soil level, bagged and returned to the laboratory for processing.

Prior to ground radiance data collection and harvesting, spectral radiance data were gathered with the Mark II hand-held radiometer from a low-altitude airplane over each of the six plant communities described above. Radiance measurements were obtained by extending the sensor head of the radiometer out the window and sampling when the desired vegetation community was directly below. Radiance measurements were obtained at an altitude of approximately 70m ± 10m at an airspeed of about 70 knots. At this low altitude, and since the investigator could lean out the window, there was no question as to what vegetation community was being sensed. Spectral radiance data were collected in duplicate for TM wavebands 3, 4 and 5, and MSS wavebands 5 and 7. Due to instrument malfunction, MSS waveband radiance data were not obtained during the May overflight.

Model Testing

A small portion of marsh on the north shore of Old Mill Creek was selected as a second testing site for the spectral radiance models. The entire marsh was divided into 30m by 30m blocks, such that sampling stations were on 30m centers throughout the marsh. The 30m grid was established with each station being staked and marked with a small piece of flagging material. The flagged stakes were to provide ground reference points so radiance data could be collected from a low-altitude aircraft within each 30m by 30m block. Unfortu-

nately, the plane velocity was too rapid to allow positive identification of each plot. Therefore, data were collected in a systematic fashion such that all major plant associations were sampled in proportion to the areal extent of each. The mission was flown on 10 August 1982.

During the two days following the overflight, ground-based spectral radiance data were collected, and biomass was harvested at each of the twenty-one ground stations. Spectral radiance data were collected in triplicate in the three TM wavebands and the two MSS wavebands. A step ladder was necessary to achieve proper instrument height above most of the brackish marsh canopies. All standing biomass from within a $0.25m^2$ frame was harvested.

Laboratory Processing of Vegetation

Each vegetation sample was first sorted into live and dead tissue, followed by sorting the live tissue into individual plant species. For most samples, only one or two species had a significant amount of biomass. A representative subsample was drawn from each of the most abundant species. The subsample was then sorted into live leaves and stems. Leaves of broad-leaf plants were separated at the petiole, such that the petiole was considered part of the stem tissue. Live biomass for *Iva frutescens* samples was considered to be only green leaf tissue. All sorted components and the remaining unsorted portion of the sample were dried at 60°C to a constant weight, weighed to the nearest 0.1g, and expressed as gram dry weight per square meter (gdw m^{-2}).

Results

A comparison of biomass estimates from harvesting and computed from ground-gathered spectral data appears in Table 3. The models used to estimate biomass from spectral data were included in the Year 1 progress report, as can be found in Hardisky (1984). With the vast majority of spectral radiance index and model combinations, the spectral radiance index estimates of total live biomass were not significantly different from the harvest biomass estimates. The species combination models for the vegetation and infrared indices were particularly good. The MSS vegetation index estimates were very similar to the TM vegetation index estimates. This is not surprising considering both indices contain essentially the same spectral information.

TABLE 3.

Old Mill Creek Brackish Marsh Biomass Predictions
August 1982 (Ground Data)

Model	Form	Vegetation Index Predicted Biomass	Vegetation Index Difference	Infrared Index Predicted Biomass	Infrared Index Difference	MSS Vegetation Index Predicted Biomass	MSS Vegetation Index Difference
Single Species[a]	L	794(12)	- 61(92)	836(44)	- 19(74)	792(60)	- 63(84)
	LN	700(69)	-155(88)	772(53)	- 83(84)	704(61)	-151(84)
Species Combination[b]	L	877(75)	22(90)	858(64)	3(81)	732(105)	-123(105)
	LN	868(72)	13(96)	925(68)	70(97)	673(103)	-182(105)
Grasses/Scirpus	L	1065(54)	210(95)*	1042(58)	187(94)	1063(49)	208(91)*
	LN	1060(77)	205(115)	1000(79)	145(110)	1039(71)	183(110)
All Species	L	952(63)	97(102)	1014(63)	159(98)	964(55)	109(96)
	LN	1020(96)	165(132)	968(86)	113(116)	970(82)	115(120)
All Species (Equal Weight)	L	695(29)	-160(74)*	553(21)	-302(66)*	---	---
	LN	997(83)	142(120)	703(49)	-152(85)	---	---

Values are means with one standard error of the mean in parentheses. Biomass units are gdw m^{-2}.

[a]Single species model for broadleaf was Acnida/Hibiscus, for gramineous S. alterniflora (both height forms), and for leafless Scirpus.

[b]Species combination model for broadleaf species was the all broadleaf species, for gramineous S. alterniflora/Typha, and for leafless Scirpus/Salicornia.

Form: L = Linear; LN = Natural Log.

Difference = Difference between spectrally estimated and harvest estimated biomass means. A negative value indicates the spectrally estimated mean was less than the harvest estimate. An asterisk indicates that spectral and harvest estimates were statistically different at the 0.05 level according to a paired t-test.

Aircraft Data

Regression models used to directly estimate total live biomass with high-altitude spectral radiance data (airplane), or to convert high-altitude data for use in models developed with ground-gathered data, are presented in Table 4. The data used to develop the models were from the 1982 seasonal sampling of the six plant communities in Old Mill Creek, Canary Creek, and the Broadkill River. Data from all community types were included in the models.

Total live biomass estimates from high-altitude spectral radiance indices, converted for use in models developed with ground data, are presented in Table 5 for each of the three spectral transformations. Infrared index estimates of total live biomass were not significantly different from harvest estimates of total live biomass for the single species and species combination models. These same models yielded biomass estimates from the MSS vegetation index and the vegetation index, which were usually significantly lower than the harvest estimates of total live biomass. Both forms of the grasses/Scirpus model and the linear form of the all species model used with the two vegetation indices provided total live biomass estimates which were very similar to harvest biomass estimates (all were not significantly different). The log form of the all species model yielded the best estimates of total live biomass when used with the infrared index. Vegetation and infrared index estimates of total live biomass using the all species (equal weight) models were all significantly lower than the harvest estimates of total live biomass.

High-altitude spectral radiance index values were used directly in models for predicting total live biomass (Table 6). The MSS vegetation index and the vegetation index values provided estimates of total live biomass which were not significantly different from harvest estimates of total live biomass. Infrared index values produced significantly higher estimates of total live biomass than were estimated by harvest techniques. Of the three spectral radiance indices tested, the vegetation index yielded the best overall estimates of total live biomass.

TABLE 4.

Regression Models for Brackish Marsh Biomass Predictions Using Spectral Radiance Data Gathered From Low-Altitude Aircraft.

Spectral Radiance Index	Type[a]	Model[b]	r^{2c}	Standard Error of Estimate	n
	C	VI = .382 + .536(AVI)	.40	.062	59
Vegetation	D	AVI = .661 + .00015(T)	.42	.073	59
	D	AVI = .119 + .102 ln(T)	.57	.063	59
	C	II = .0954 + .863(AII)	.58	.050	59
Infrared	D	AII = .672 + .0010(T)	.35	.055	59
	D	AII = .349 + .0618 ln(T)	.42	.052	59
MSS	C	MVI = .371 + .522(AMVI)	.27	.074	45
Vegetation	D	AMVI = .657 + .00012(T)	.31	.071	45
	D	AMVI = .135 + .0941 ln(T)	.38	.067	45

[a]C = A model to convert spectral radiance indices gathered from low-altitude aircraft to comparable ground-gathered index values for substitution into models developed with ground-gathered data.

D = A model which uses aircraft-gathered spectral radiance indices directly to estimate total live biomass.

[b]VI = Vegetation Index, Ground
AVI = Vegetation Index, Aircraft
II = Infrared Index, Ground
AII = Infrared Index, Aircraft
MVI = MSS Vegetation Index, Ground
AMVI = MSS Vegetation Index, Aircraft
T = Total Live Biomass (gdw m^{-2}).

[c]r^2 = Coefficient of Determination.

TABLE 5.

Old Mill Creek Brackish Marsh Biomass Predictions
August 1982
(Aircraft Data Converted for Use in Ground-Developed Models)

		Vegetation Index		Infrared Index		MSS Vegetation Index	
Model	Form	Predicted Biomass	Difference	Predicted Biomass	Difference	Predicted Biomass	Difference
Single Species[a]	L	609(82)	-246(70)*	870(31)	15(49)	558(79)	-297(67)*
	LN	519(55)	-336(52)*	753(27)	-102(49)	498(55)	-357(53)*
Species Combination[b]	L	764(49)	- 91(49)	931(54)	76(57)	577(85)	-278(73)*
	LN	661(44)	-194(44)*	927(24)	71(50)	500(74)	-355(65)*
Grasses/<u>Scirpus</u>	L	928(22)	73(55)	1075(11)	220(55)*	852(44)	- 3(59)
	LN	818(27)	- 37(55)	983(16)	128(56)*	750(57)	-105(61)
All Species	L	794(25)	- 61(55)	1050(12)	195(55)*	728(49)	-127(62)
	LN	709(32)	-146(56)*	941(17)	86(56)	641(50)	-214(63)*
All Species (Equal Weight)	L	622(12)	-233(53)*	565(4)	-290(54)*	---	---
	LN	732(28)	-123(55)*	697(10)	-158(55)*	---	---

Values are means with one standard error of the mean in parentheses. Biomass units are gdw m^{-2}.

[a]Single species model for broadleaf was <u>Acnida/Hibiscus</u>, for gramineous <u>S. alterniflora</u> (both height forms), and for leafless <u>Scirpus</u>.

[b]Species combination model for broadleaf species was the all broadleaf species, for gramineous <u>S. alterniflora/Typha</u>, and for leafless <u>Scirpus/Salicornia</u>.

Form: L = Linear; LN = Natural Log.

Difference = Difference between spectrally estimated and harvest estimated biomass means. A negative value indicates the spectrally estimated mean was less than the harvest estimate. An asterisk indicates that spectral and harvest estimates were statistically different at the 0.05 level according to a paired t-test.

TABLE 6.

Old Mill Creek Brackish Marsh Biomass Predictions
August 1982
(Aircraft Data With Models For Aircraft Data)

Model	Form	Harvest Biomass	Predicted Biomass	Difference
Vegetation Index	L	855(54)	924(41)	69(62)
	LN	855(54)	802(49)	- 53(64)
Infrared Index	L	855(54)	1214(18)	359(57)*
	LN	855(54)	1346(38)	490(65)*
MSS Vegetation Index	L	855(54)	603(126)	-252(122)
	LN	855(54)	697(94)	-158(96)

Models correspond to the Type D Models in Table 4.

Values are means of 21 plots with one standard error in parentheses.

Biomass units are gdw m^{-2}.

Difference = Difference between spectrally estimated and harvest estimated biomass means. A negative value indicates the spectrally estimated mean was less than the harvest estimate. An asterisk indicates that spectral and harvest estimates were statistically different at the 0.05 level according to a paired t-test.

ANNUAL NET AERIAL PRIMARY PRODUCTIVITY (NAPP) ESTIMATE FOR A SPARTINA ALTERNIFLORA MARSH USING SPECTRAL RADIANCE DATA

Study Design

A 22 ha portion of the Canary Creek salt marsh in Lewes, Delaware, was selected for study. The marsh was dominated by monospecific stands of *Spartina alterniflora* Loisel. Six transects extending from the creek edge to the upland were established. The transects were spaced approximately 210m apart over the entire 22 ha marsh, and stations were designated every 30m along each transect. A total of forty stations for the whole marsh was established. By establishing stations in a systematic manner along transects, a representative cross section of *S. alterniflora* height forms occurring within the marsh was sampled. Beginning on May 15 and continuing every three weeks until October 9, four stations from each transect were selected for harvesting using a table of random numbers. A total of 192 plots were sampled during the season. No more than five days prior to harvesting, a GSFC Mark-II hand-held radiometer was used to measure canopy radiance directly over each area to be harvested. The radiometer was spectrally configured to simulate bands 3, 4 and 5 of the Landsat Thematic Mapper.

Harvesting Procedures

After collection of radiance data, all vegetation (including standing dead material) within a $0.25m^2$ frame was clipped at soil level at each station. The plant material was bagged and returned to the laboratory for processing. A one-third subsample (by wet weight) was drawn from the vegetation samples and sorted into live and dead components. A representative subsample was sufficient to determine relative proportions of live and dead tissue, and by retaining the entire $0.25m^2$ sample for biomass determination, the best estimate of biomass, considering the heterogeneous distribution of biomass within the area sampled, was preserved. Proportions of live and dead tissue determined from the subsample were then extrapolated to the entire biomass sample. All plant material was dried at 60°C to a constant weight, weighed to the nearest 0.1g, and expressed as grams dry weight per square meter (gdw m^{-2}).

NAPP Estimation

The regression models equating *S. alterniflora* biomass and spectral radiance indices used for this study were developed during the 1980 growing season (Hardisky et al. 1983b). These models included both short and tall form *S. alterniflora* sampled from June through November using the hand-held radiometer. Using the mean biomass values computed from the model and estimated from harvest data, annual NAPP was calculated for the *S. alterniflora* salt marsh. Established NAPP calculation techniques used widely in salt marsh systems were employed (Table 7). There has been some discussion as to the adequacy of these techniques, and we recognize the shortcomings of each. However, these techniques are widely used and yield values comparable to other studies.

Annual NAPP estimates for the Canary Creek marsh are compiled in Table 7. If all height forms of S. alterniflora are considered together, the vegetation index estimates ranged from 0% to 11% higher than the harvest estimates. The infrared index estimates ranged from 8% to 18% lower than the harvest estimates. On the average, the spectral radiance index estimates of NAPP were ±10% of the NAPP estimate computed from harvest data.

The close agreement between biomass and NAPP estimates obtained by remote sensing and harvest techniques is encouraging. The remote sensing technique has several important advantages over harvesting. In this study, we estimated that eight man-days were required to clip, sort and weigh 24 grass samples. The same number of samples could be monitored with the radiometer in about 0.25 man-days. Another advantage of the remote sensing technique was that, with the small time requirement, many more stations could be sampled. The range of biomass per unit area encountered in marsh plant communities can be large, indicating a large number of samples may be necessary to adequately describe the vegetation of the whole marsh. Spectral radiance data can be gathered rapidly over a large area, suggesting that a more accurate biomass estimate for the entire marsh is possible without laborious harvesting. The major disadvantages of using the remote sensing technique to estimate NAPP were that sampling could only be undertaken during sunny conditions, for only four hours per day, and only during a tidal stage when the marsh surface was not flooded.

TABLE 7.

Annual Net Aerial Primary Productivity Estimates for *Spartina alterniflora* in Canary Creek Marsh[a]

Method	All Height Forms			Short Form			Tall Form		
	Harvest[b]	VI[c]	II[d]	Harvest	VI	II	Harvest	VI	II
Peak Standing Crop	540	600	489	372	411	384	826	913	664
Milner and Hughes (1968)	540	600	490	372	420	390	826	913	664
Morgan (1961)	540	600	496	405	411	415	826	913	664
Smalley (1958)	601	603	493	505	441	397	980	974	664

[a]Units on production values are gdw $m^{-2}yr^{-1}$.

[b]Harvest denotes NAPP computed from harvested data.

[c]VI denotes NAPP computed from vegetation index data.

[d]II denotes NAPP computed from infrared index data.

CONCLUSIONS

Regression models equating S. alterniflora biomass with ground gathered spectral radiance data were successfully used to nondestructively estimate salt marsh biomass. Biomass estimates predicted from the vegetation index or from the infrared index models compared favorably with concurrent biomass estimates determined from traditional harvest techniques. The infrared index yielded estimates of mean live and mean total biomass closest to harvest estimates of mean live and mean total biomass from May through July in tall form S. alterniflora and from mid-June through October in short form S. alterniflora. The vegetation index yielded the best mean biomass estimates from August to October in tall form communities. Although mean biomass estimates from remote sensing and from harvesting were reasonably similar throughout the growing season, the best agreement between individual spectral radiance index and harvest biomass estimates was during the middle of the growing season.

Dead biomass and soil background reflectance are at times significant contributors to canopy radiance. For the typical case in the marsh studied, dead biomass and soil background reflectance attenuated the vegetation index, but only dead biomass significantly attenuated the infrared index. Low live biomass areas favored mean biomass predictions with the infrared index, and high live biomass areas favored mean biomass predictions with the vegetation index. The accuracy of model-predicted biomass compared to harvest estimated biomass computed over the entire growing season was greater for the vegetation index than for the infrared index in both height forms. Changes in the position and orientation of dead biomass within the canopy and a reduction in soil background reflectance as the growing season progressed caused vegetation index biomass estimates to be low during the first half of the growing season, and similar or high during the latter half of the growing season, compared to harvest biomass estimates.

Modeling the relationship between spectral radiance indices and live aerial biomass in brackish marsh plant communities required consideration of diverse morphologic characteristics among plants residing in the same community. Canopy architecture plays a decisive role in the interception of incoming radiation and, therefore, is an extremely important consideration when interpreting spectral radiance signatures from wetland plant canopies. We have determined that wetland vegetation canopies can be characterized as being broadleaf, gramineous or leafless, with each canopy type possessing unique reflectance characteristics. We have been able to predict biomass to within 10% of harvest biomass estimates using regression models based on spectral radiance data.

Regression models were used to directly estimate total live biomass with aircraft spectral radiance data, and to convert high-altitude data for use in models developed with ground-gathered data. The vegetation index values provided estimates of total live biomass which were not significantly different from harvest estimates of total live biomass. Aircraft infrared index values produced significantly higher estimates of total live biomass than were estimated by harvest techniques. Of the three spectral radiance indices tested, the vegetation index yielded the best overall estimates of total live biomass.

Several mangrove swamps on the Pacific coast of Costa Rica near Puntarenas were selected for study. As expected, the only canopy parameter significantly correlated with radiance values was live leaf biomass. Mangrove canopies can be classified as broadleaf canopies, suggesting that most leaf surfaces are in the horizontal plane and that little biomass below the green canopy is illuminated. The TM vegetation index was the best spectral index for biomass quantification in the mangrove canopies. Considering the spectral complexity of woody broadleaf canopies, the strong association between spectral radiance and leaf biomass is encouraging.

Remote sensing techniques hold much promise for rapid nondestructive estimates of marsh biomass. Repetitive biomass estimates from spectral data can be translated into annual net aerial primary production estimates. Considering the much larger number of biomass estimates which can be computed from spectral data collected with a radiometer, as compared to the number which can be estimated by harvesting in an equal time period, remote sensing estimates of whole marsh biomass and NAPP appear to be more representative than estimates based on conventional harvesting techniques.

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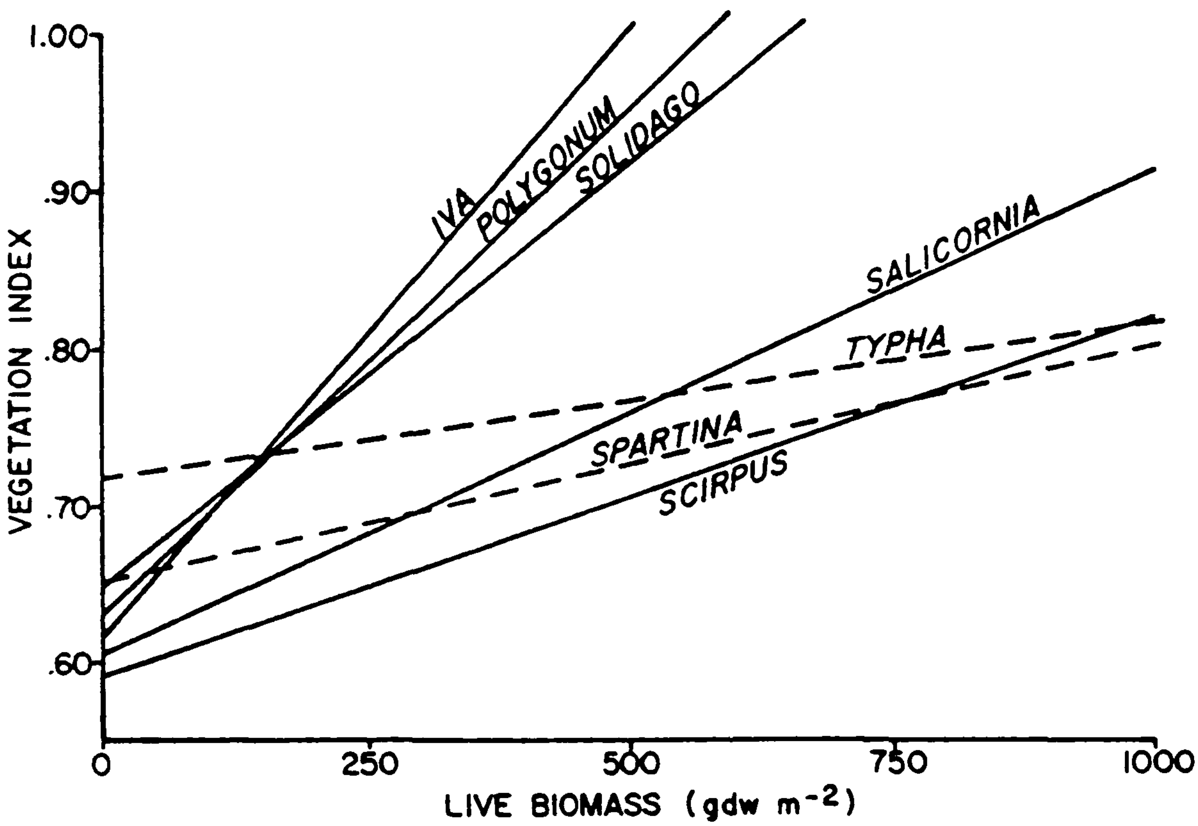

Figure 1. Relationship between live biomass and the vegetation index for a variety of wetland plants representing broadleaf, gramineous and leafless canopies.

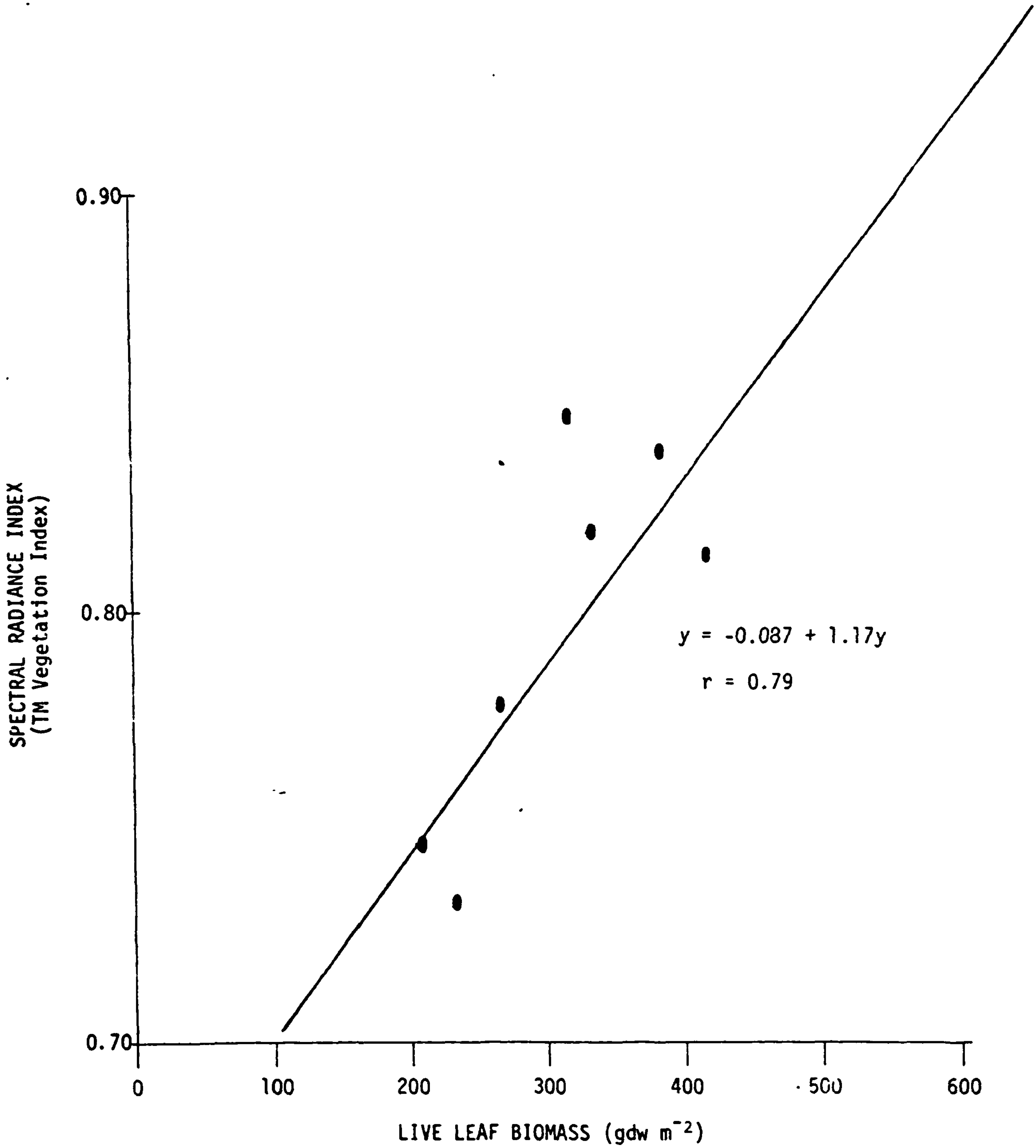

Figure 2. Mangrove canopy radiance as a function of live leaf biomass.